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# The costs of uncoordinated infrastructure management in multi-reservoir river basins

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## Abstract

Though there are surprisingly few estimates of the economic benefits of coordinated infrastructure development and operations in international river basins, there is a widespread belief that improved cooperation is beneficial for managing water scarcity and variability. Hydro-economic optimization models are commonly-used for identifying efficient allocation of water across time and space, but such models typically assume full coordination. In the real world, investment and operational decisions for specific projects are often made without full consideration of potential downstream impacts. This paper describes a tractable methodology for evaluating the economic benefits of infrastructure coordination. We demonstrate its application over a range of water availability scenarios in a catchment of the Mekong located in Lao PDR, the Nam Ngum River Basin. Results from this basin suggest that coordination improves system net benefits from irrigation and hydropower by approximately 3–12% (or US\$12–53 million/yr) assuming moderate levels of flood control, and that the magnitude of coordination benefits generally increases with the level of water availability and with inflow variability. Similar analyses would be useful for developing a systematic understanding of the factors that increase the costs of non-cooperation in river basin systems worldwide, and would likely help to improve targeting of efforts to stimulate complicated negotiations over water resources.

 Online supplementary data available from [stacks.iop.org/ERL/9/105006/mmedia](http://stacks.iop.org/ERL/9/105006/mmedia)

Keywords: hydroeconomic models, water resources planning and management, cooperation, reservoir coordination, irrigation, hydropower, Mekong

## 1. Introduction

With increasing global water scarcity and the reality of climate change disruptions to hydrological systems, there is growing international recognition of the importance of cooperation for effective water resources management. Part of the focus on improving cooperation stems from concerns over potential future water-related conflicts (Homer-Dixon 1994),

though research indicates that violent conflict over this resource has historically been rare (Wolf 1998). A somewhat different argument is that cooperation of planning and operation of water-related infrastructure can produce gains in economic efficiency (Howe *et al* 1986, Rogers *et al* 2002, Sadoff and Grey 2002). The emergence of concepts based on Integrated Water Resource Management (IWRM) and benefit-sharing, as well as norms for water sharing in international law, reflect this trend (GWP 2000). In discussions about cooperative management of water resources, water infrastructures, and dams in particular, often receive considerable attention. Such projects often generate multipurpose benefits



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and are crucial for providing flexibility for coping with variability, but are typically designed in order to maximize specific objectives, for example revenues from energy generation (Tilmant *et al* 2010). Indeed, the traditional design paradigm for dams is often heavily critiqued for not adequately considering spillovers to other economic sectors, downstream agents, or ecosystems (both positive and negative), even when these are acknowledged in planning documents (WCD 2000, Labadie 2004, Davis 2007).

Despite the prominence of the view that cooperation in water resources management is desirable, unilateral water resources development that ignores the ‘system value of water’—or aggregate value across all uses in a watershed—remains the norm in most basins (Sadoff and Whittington 2002, Whittington *et al* 2013). In the absence of formal agreements between riparians sharing water resources, there is a short-term incentive to pre-emptively lay claim to unused water resources by pursuing projects that are perhaps sub-optimal in the long term (Wu and Whittington 2006). In addition, there is remarkably little quantitative analysis and understanding of the economic value and distribution of gains from cooperation—as we discuss further in this paper. There may also be problems with placing undue emphasis on the value of coordination, if for example overestimation of interdependence across users rationalizes the anxiety and fear of downstream riparians regarding the effects of proposed large upstream infrastructures, thereby impeding development (Wu *et al* 2013). Also complicating discussions over water are transaction costs; the spatio-temporal complexity and variability of the resource, both of which are increasing with climate change; the fact that development planning affecting water resources is often undertaken outside the water sector; and political obstacles to cooperation (Elhance 2000, Wu and Whittington 2006).

Whatever the reason for these coordination failures, a better understanding of the benefits of cooperation relative to unilateral infrastructure development and management appears critical to negotiating and achieving more efficient outcomes. This paper outlines and demonstrates an approach for considering these benefits. Section 2 presents a basic framework for assessing the costs of non-coordination in river basins with multiple users, and considers the nature of past efforts to measure such costs (or alternatively, to estimate the value of cooperation). In section 3, we present an application that focuses on the Nam Ngum Basin, a sub-catchment of the Mekong located in the People’s Democratic Republic of Lao (hereafter Lao PDR). The paper ends with consideration of the broader implications of this application, and a discussion of research questions and challenges related to evaluation of the costs of non-cooperation.

## 2. Using hydro-economic modeling to consider the costs of non-cooperation in river basins

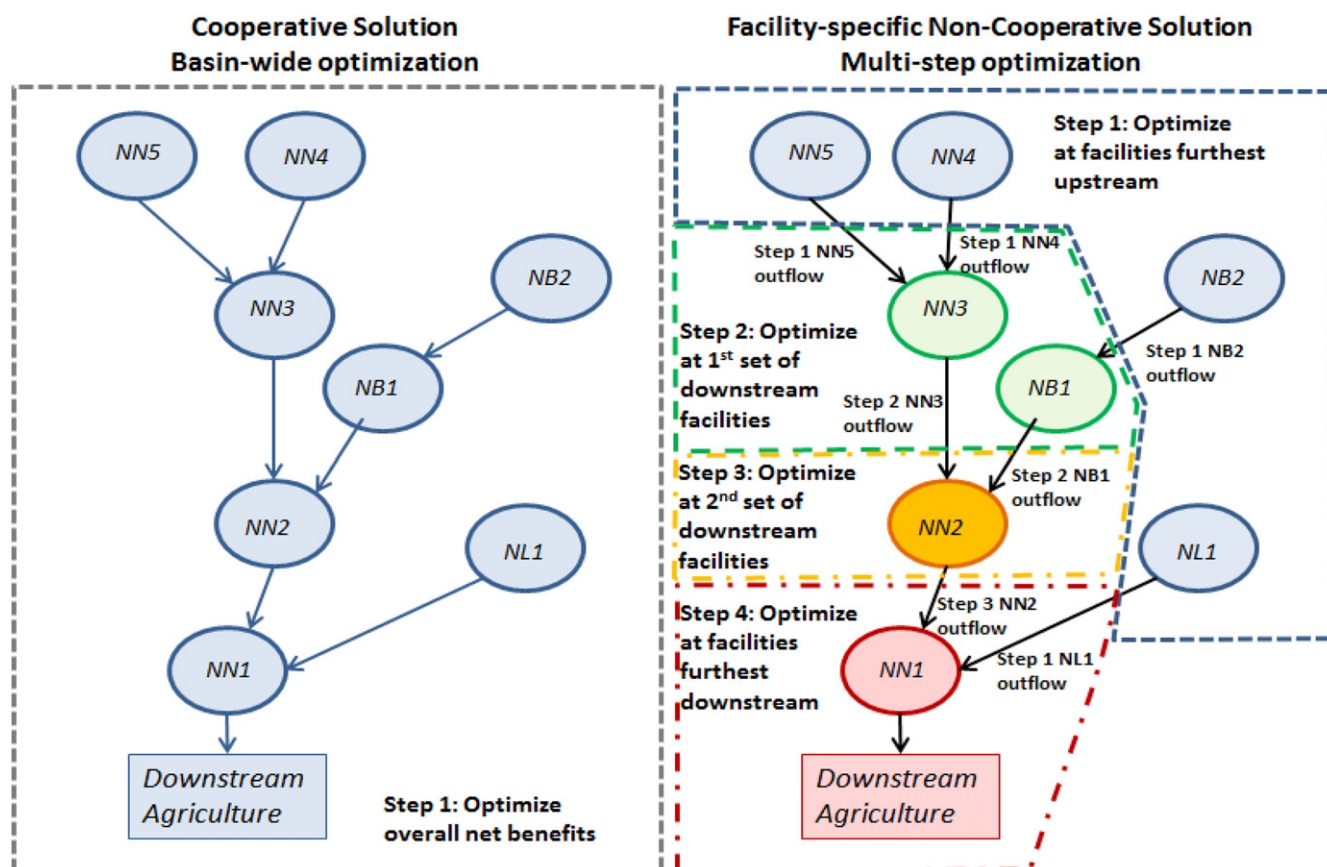
### 2.1. Hydro-economic framework

This section describes a hydro-economic approach for estimating the costs of non-cooperation in water resource

systems, or conversely, the net economic benefits of integrated management of water resources at the basin-scale. Hydro-economic models are node-link conceptualizations of specific water resource systems that include water balance components (e.g. river flows, evaporation and outflows from surface water bodies, natural groundwater recharge and discharge, and return flows), and built water control structures (canals, reservoirs, treatment plants, pumping stations, etc) (Maass *et al* 1962). In contrast to engineering models that minimize costs or maximize particular outputs (e.g. water availability for irrigated crops), hydro-economic models determine how units of water should be allocated across time, space, and uses to produce the greatest overall economic net benefit (Harou *et al* 2009). Such models have been applied widely for estimation of tradeoffs across users and sectors encompassing human consumption and production of goods and services, recreation, and production of environmental services and ecological habitat (Jenkins *et al* 2004, Medellín-Azuara *et al* 2007, Harou *et al* 2009).

The value of using hydro-economic models for assessing the costs of non-cooperation stems from their ability to identify an efficient and spatially-differentiated allocation of water against which non-cooperative management alternatives can be compared (Tilmant and Kinzelbach 2012). In our conceptualization of this problem, the potential gains from cooperation in a basin can be obtained by comparing the net economic benefits of water allocations under two distinct approaches of infrastructure development and water management. The first approach, hereafter referred to as the ‘basin-wide approach,’ assumes that construction and operation of new and existing control infrastructures and water allocated to different uses in a basin are coordinated across space and over time to maximize economic net benefits, and is generally consistent with the optimization methods implemented using traditional water resources planning models. This approach represents an upper bound on the economic production that could be achieved, given physical, legal, or other constraints (Cai 2008). Such planning models have previously been applied to the Mekong which encompasses the Nam Ngum Basin considered in this paper (Ringler *et al* 2004, Ringler and Cai 2006).

The second optimization approach, which we call the ‘facility optimizer approach’, disaggregates the model into a set of facility-specific economic agents (hydroelectric dams in our example) who seek to maximize economic net benefits at their specific locations given the actions of others located upstream in the basin (Giuliani and Castelletti 2013). The problem is then solved sequentially. In stage 1, upstream dams or water users manage reservoir releases or water abstractions over the course of a year to optimize their location-specific economic returns without accounting for downstream impacts. In stage 2, those located immediately downstream of the stage 1 users optimize their own behavior on the basis of the water releases they receive from those upstream agents. The upstream water releases, obtained in stage 1 of the optimization routine, are thus treated as exogenous inputs to the stage 2 agents’ decision problem. This process then continues with solution of a series of



**Figure 1.** Conceptual diagram comparing optimization methods for the basin-wide (cooperative) approach and the multi-stage facility optimizer (non-cooperative) approach in the Nam Ngum Basin application. Note that downstream agriculture is viewed as an objective of the Nam Ngum 1 (NN1) facility in this example.

optimization problems until the downstream end of the basin is reached. It thus represents the least cooperative river basin case possible, because upstream agents make decisions entirely independently of downstream demands. Figure 1 provides a conceptual diagram of this modeling framework, with a very simple node schematic of the infrastructures included in this analysis (discussed in section 3.1), investments which are made primarily for hydropower and agricultural production. On the left-hand side, reservoir operations are coordinated, yielding the basin-wide solution. The diagram on the right represents the facility optimizer approach in which dams are independently operated and different colors represent different stages of the optimization routine.

Several points should be made about this approach. First, its main advantage is that it more accurately represents independently managed dam facilities, and the reality that downstream water users are often forced to conform to the timing and quantity of upstream reservoir releases (Bernauer 2002). Comparing the results from these distinct optimization approaches provides a proxy for the net economic benefits to coordination, which can be assessed against the potential transaction costs that such management might entail. Second, the methodology can accommodate a variety of infrastructure project types (e.g., hydropower dams, irrigation infrastructures, water transfers) and operating rules, and can

be adapted to consider changes in the management of existing and/or new potential infrastructures. It produces information on the economic value of cooperation that could facilitate negotiations and more efficient use of the resource, as well as re-consideration of existing regulatory constraints. Third, it allows examination of the distribution of relative economic gains and losses across users when moving from a facility-level to a basin-wide approach. Such information sheds light on the compensation that might be necessary to encourage upstream users to adjust their behavior in order to achieve the optimal basin-wide solution. Yet it must be noted that in many cases, there may already be partial coordination between users, or their behavior may otherwise be regulated. In fact, the facility optimizer approach could be extended to allow for partial coordination in which individual agents iteratively establish priorities for collaboration with other agents until an equilibrium outcome is achieved (Yang *et al* 2009, Yang *et al* 2011). In addition, such partial coordination is already reflected in any model that works from a set of pre-determined infrastructure design parameters, since decision makers usually consider a variety of impacts from such projects. Partial coordination can also be accommodated by collapsing the stages of the facility optimizer approach according to the realities of a basin's prevailing water management regime. Similarly, to the extent that such rules are known, regulation can be imposed on the system through

inclusion of behavioral constraints, for example on minimum releases or seasonal production targets; this is in fact the approach we adopt in this paper's application.

## 2.2. Existing studies on the costs of non-cooperation

Optimization models have been extensively applied to problems of reservoir coordination in the literature, mostly for operations of existing infrastructure (Yeh 1985, Labadie 2004, Anghileri *et al* 2012). For planning purposes, such models typically also incorporate the economic benefits associated with optimal management of new potential infrastructure, most commonly for irrigation or hydropower production (Cai *et al* 2002, Goor *et al* 2010). The basic objective of all such models is to identify release decisions that maximize output or benefits from system operation over a given planning period.

Few applications of such models have explored how user-specific objectives may deviate from the optimal system-wide solutions, though several do so indirectly by measuring the economic value of cooperation relative to some constrained status quo (Fisher 2005, Whittington *et al* 2005). One shortcoming in such analyses is that infrastructure or allocations in the non-cooperative state are generally taken to be fixed or to follow a specific trajectory over time, which may not be realistic; in addition, few studies consider unilateral developments across multiple sectors or the implications of multi-sectoral objectives.<sup>1</sup> Tilmant and Kinzelbach (2012) provide a different example for the Zambezi that allows for unilateral development in irrigation or hydropower that stems from different country-level advantages in these two domains. They estimate that the cost of non-cooperation may reach \$350 million per annum, equivalent to 10% of the annual benefits derived from the system. In the same basin, Giuliani and Castelletti (2013) apply an agent-based approach that considers how coordination and information-sharing can improve outcomes for downstream users given existing infrastructure, even if operations are not fully coordinated. In this case, downstream users can model upstream riparians' optimal responses and adapt their own operations accordingly. Finally, Yang *et al* (2011) use their agent-based approach to consider the potential gains from water trading (compared to no regulation and a specific regulation regime) in the Yellow River.

It is worth noting that the cost of non-cooperation (and conversely the benefit of cooperation) will not in general be equitably shared across water users and operators of river-basin infrastructure of different types; Tilmant and Kinzelbach (2012) suggest this is a major obstacle toward the efficient sharing of the basin's water resources. In fact, similar observations in other basins have motivated game theoretic analyses that may shed light on the feasibility of coordination (Rogers 1969). For example, building on the results in Whittington *et al* (2005), Wu and Whittington (2006) assess the incentive compatibility of different coalitions relative to

the non-cooperative status quo with fixed infrastructure. Though we do not conduct distributional or game theoretic analyses in this paper, we consider that such analyses would be useful when combined with information on the economic gains of coordination.

Building upon previous applications, our study estimates the benefits to cooperation through a comparison of the alternative optimization methods presented above. We extend beyond Giuliani and Castelletti's (2013) comparison of the value of information sharing alone by assessing the gains from cooperative management across scenarios of water availability. Our approach also differs from that in Tilmant and Kinzelbach (2012) because we allow for the endogenous expansion of irrigation and consider the gains from coordination of flood control.

## 3. Application to the Nam Ngum basin reservoir coordination problem

### 3.1. Description of the application

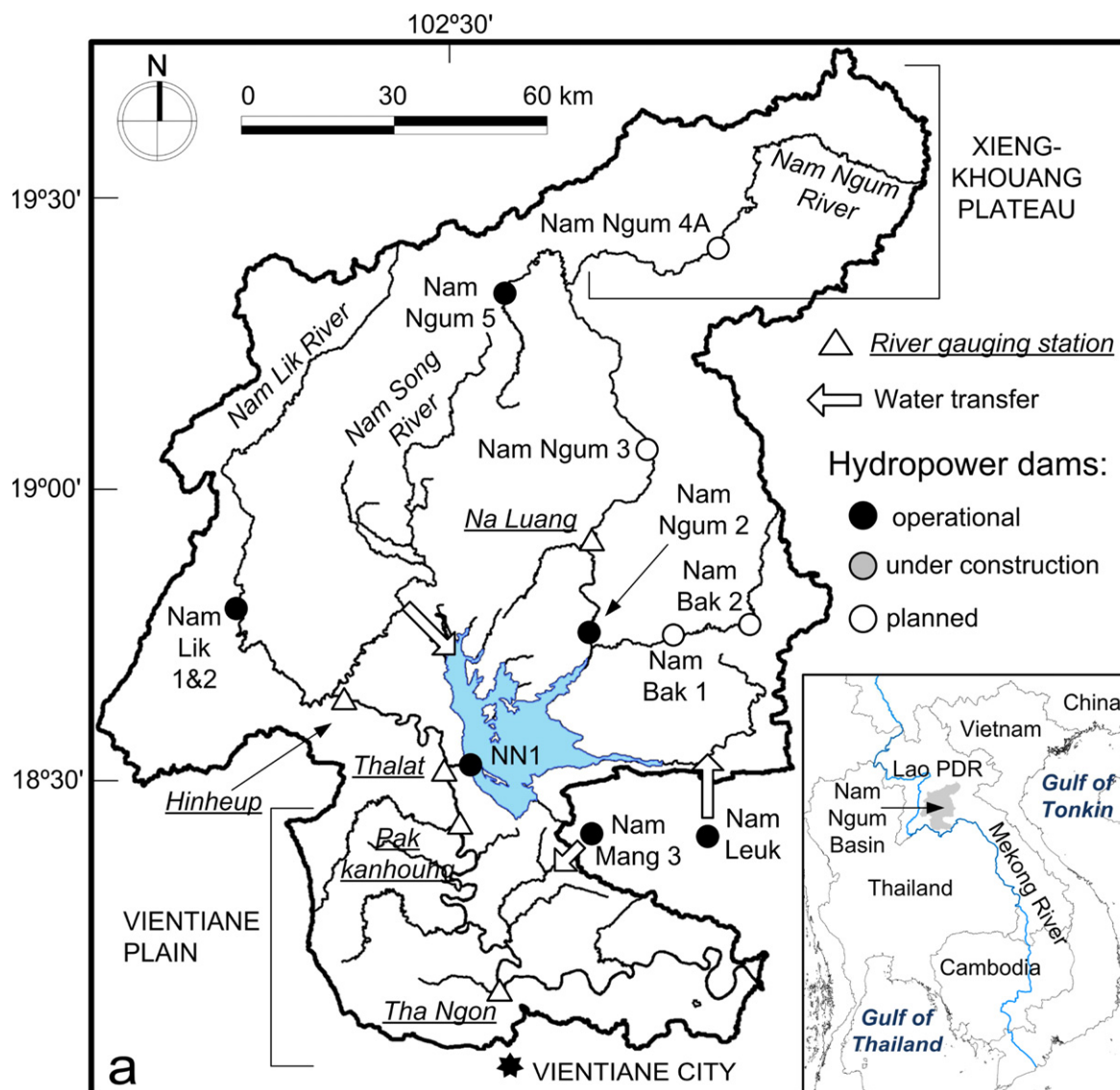
Our application focuses on the Nam Ngum River Basin in Lao PDR. Covering 16 800 km<sup>2</sup>, the Nam Ngum Basin is home to roughly 500 000 people, representing approximately 9% of Lao PDR's total population (WREA 2008). It contributes a mean annual flow of 23 km<sup>3</sup>/year to the Mekong River, or 4% of the latter's mean annual flow and up to 15% of dry season flow (Lacombe *et al* 2014). The vast majority of existing food production and expansion potential from the Nam Ngum is located in the Vientiane Plain, which comprises the nation's largest area of agriculturally viable land (WREA 2008). Several new irrigation projects are in various stages of planning as part of a larger government strategy to turn the basin into a national and regional production area for rice and vegetables. The most ambitious of these proposals would increase irrigated area by a factor of 5, or 100 000 hectares (Geotech 2012).

Like many rivers in Lao PDR and in the Mekong Basin, the Nam Ngum attracts the most interest for future development because of its hydropower potential (Hirsch 2010). The basin already includes four dams built primarily for energy production, three of which were completed in the last five years (representing 835 MW of installed capacity); all of these dams are operated independently. Six more are in various stages of planning (EPD 2012, Lacombe *et al* 2014). These developments are seen by many as critically important for meeting the currently growing energy demand in the lower Mekong Basin (Yu 2003), but they raise questions and concerns about other potential tradeoffs, for example with water supply to downstream irrigation, or for flood protection or ecological flows (Middleton *et al* 2009). Figure 2 provides a map of the Nam Ngum Basin that shows the location of existing and planned dams included in our analysis.

We apply a nonlinear optimization model for assessing the economic benefits of hydropower generation and water allocation to irrigated agriculture in the basin. The objective function of this monthly model maximizes the net returns to

<sup>1</sup> Whittington *et al* (2005) argued that this assumption was appropriate in the case of the Nile in 2005 because the countries required cooperation to access sufficient international capital for the large investments being considered. Since 2005, the situation has however evolved.





**Figure 2.** The Nam Ngum Basin, including current and planned hydropower dams.

hydropower (monthly revenue less capital costs) and irrigated agricultural profits over an annual period (and thus assumes full hydrological foresight over this period). The model ensures hydrologic continuity (water balance). Also, it includes constraints that require a storage buffer for flood control and environmental flow requirements, though the economic benefits of flood control and ecological protection are not incorporated into the objective function due to lack of valuation data relating to these aspects. Other constraints govern the availability of agricultural land and seasonal energy demand (Bartlett *et al* 2012).<sup>2</sup> This formulation thus allows determination of the marginal opportunity costs (or shadow values) associated with relaxing those constraints (e.g. relaxing a minimum release constraint). The model

includes spatially-disaggregated irrigable potential across the basin, as well as all existing and planned dams except for Nam Leuk and Nam Mang 3, and the run-off-river Nam Lik 1 dam, for which dam-specific parameters were not available. Irrigation expansion is a key decision variable; the model thus chooses how much land should be irrigated, weighing the costs of canal expansion and cultivation against the benefits of crop production for newly irrigated land.

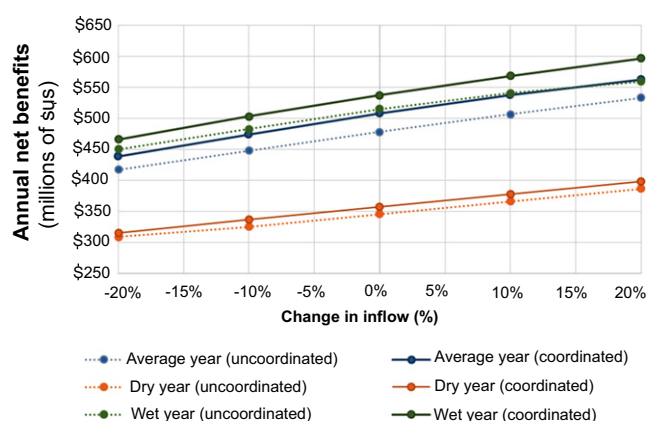
We consider the value of coordination based on the basic approach described previously in section 2.1. Under full coordination, the model solves for the optimal solution subject to a basin flood control buffer (we explore a range from 0 to 9% of system storage across sensitivity analyses). This is reasonable given that flood protection in this basin is most needed in the floodplain downstream of the full set of dams; thus a system buffer would provide reservoir managers maximum flexibility for storing excess flows during extreme events. In the absence of coordination, on the other hand, we assume that the flood control buffer would have to be

<sup>2</sup> An abbreviated summary of the objective function and constraints can be found in the supplementary materials provided with this paper. A more complete description of the model can be found in Bartlett *et al* (2012), available at: <http://sites.nicholasinstitute.duke.edu/environmentaleconomics/working-paper-series/>.

**Table 1.** Economic benefits with and without coordination across hydrological conditions (million US\$/yr).

	Dry year	Average year	Wet year
Basin-wide optimization (cooperative solution)	358	508	537
Facility-specific optimization (non-cooperative solution)	346	478	515
Gain in benefits with cooperation	12	30	23
Per cent difference with non-cooperation	−3.4%	−6.3%	−4.4%

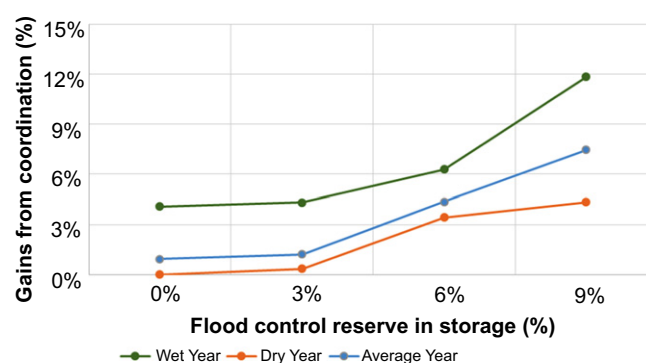
Notes: assumes a flood control buffer equivalent to 6% of storage capacity; row 3 is computed as row 1−row 2, with apparent inconsistencies due to rounding.


**Figure 3.** Sensitivity of economic net benefits to changes in flows (with flood control buffer equivalent to 6% of storage).

maintained by the dam furthest downstream in the system (Nam Ngum 1—NN1).

Southeast Asia and the Mekong region are frequently cited as highly vulnerable to climate change (Samson *et al* 2011, Watson *et al* 2013). In order to understand how the benefits of coordination vary with hydrological conditions, we model dry, normal, and wet years as selected from the range of available historical flows covering the period 1967–2004. The flow difference across dry (minimum flow into the Mekong) and wet (maximum) flows in this time series encompasses the range of projections for climate change over the Nam Ngum (Lacombe *et al* 2014). Still, to further examine the potential interaction of more extreme climate conditions with low and high flow variability, and based on the lack of agreement over potential changes described in the literature (WREA 2008, Kingston *et al* 2011, Lauri *et al* 2012, Thompson *et al* 2013), we also consider the sensitivity of our results (for each of these three years) to uniform and basin-wide inflow changes ranging from −20% to +20%.<sup>3</sup> As the Nam Ngum is an important tributary to the Mekong in terms of dry season flow, the scenarios presented here allow us to consider how flows into the larger river would be affected by these collective developments, with and without cooperation, across a range of potential future climate conditions.

<sup>3</sup> We would argue that this sensitivity approach is appropriate because our focus is not on the use of climate change projections for hydrological analysis, and because of the lack of consensus on impacts over this region.

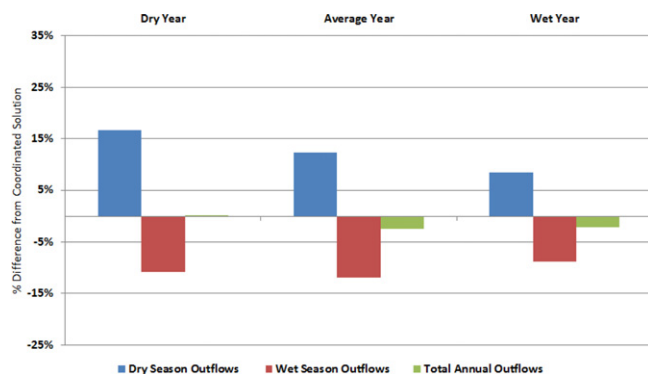

**Figure 4.** Sensitivity of coordination benefits to flood control requirements.

### 3.2. Results

There are important declines in overall economic returns when dams are independently managed compared to the basin-wide optimal solution (table 1). While the literature supports the idea that coordination should improve economic outcomes, the comparison of results from these alternative modeling approaches provides a more straightforward estimate of the cost of uncoordinated management. Intuitively, overall economic net benefits increase with water availability and inflow (figure 3); somewhat surprisingly the costs of uncoordinated operation do as well. When water is limited in the basin, upstream dams have less flexibility to make dry season adjustments to operating rules, which decreases economic returns at downstream locations. As water availability increases and upstream dams are able to adjust dry season operations, we find increased gains from coordination with downstream dams. Variability plays a role as well; since the average year has the most variable flows across months, the gains from coordination are greater than for the wet year which has more consistent (high) flows.<sup>4</sup>

Perhaps because there is no shortage of water required to meet the irrigable potential in the Nam Ngum (Lacombe *et al* 2014), we find that the difference in economic benefits is driven entirely by a shift in hydropower output (there is no change in net irrigation profits) (table 2). In addition, for the dams located in the upstream part of the basin (Nam Ngum 5—NN5, Nam Ngum 4—NN4, Nam Lik 1—NL1 and Nam Bak 2—NB2), there is little net change in annual hydropower

<sup>4</sup> The hydrographs depicting optimized streamflow at the confluence with the Mekong in each of these hydrologic years are provided in the supplementary materials.



**Figure 5.** Per cent change in total Nam Ngum Basin outflows into the Mekong (facility-specific solution relative to basin-wide cooperative solution, with 6% flood storage buffer).

generation between the cooperative and non-cooperative solution (less than 2% for most cases). Instead, the difference in outcomes is driven by decreased hydropower generation at the larger dams (Nam Ngum 2—NN2 and NN1) located in the downstream part of the system. This is due to both adjustments in the timing of releases from upstream dams and shifting management of releases from NN1 in response to flood control requirements. Although total hydropower does not change substantially for NN4, NN5, NL1, and NB2 over the full year, there are large seasonal adjustments in production (table 2; seasonal results shown for average water availability). Under the facility-specific approach, upstream dams reduce dry season turbine releases in an effort to maintain high head such that hydropower production—a multiplicative function of head and outflow—remains high during the subsequent wet season. This reduction in turbine releases has a cascading effect downstream, as inflows to larger downstream dams decline in the dry season. Additionally, individual dams are forced to hit seasonal energy demand targets in this case, whereas the cooperative solution manages all dams simultaneously to conform to demand schedules.

These inefficiencies are further exacerbated when flood control requirements increase and cannot be coordinated across dams (figure 4). In the absence of any flood control requirement, the gains from coordination range from about 0–4% across hydrological years, mostly driven by the effects described above. As flood control requirements rise to 9% of storage, the gains from coordination rise to 4–12% (and are lower under dry and less variable hydrologic flows). Coordinated management of flood control allows the system to maintain the flood buffer where the marginal cost of lower storage (in terms of lost hydropower) is smallest, a cost that varies across dams.

Finally, changes in release patterns from upstream dams reduce outflow and dry season water availability in the non-cooperative case, which increases evaporation at upstream dams. The combined impact of reduced dry season outflows and increased evaporation at upstream dams lowers total basin outflows into the Mekong River over the course of the simulation year for the average and wet hydrologic scenarios (figure 5).

For each of the dry, average and wet years, total basin outflows increase substantially in the dry season as NN1 increases turbine releases in the early months of the simulation to hit the total basin flood control target (figure 5). Wet season outflows then decrease for the uncoordinated cases as lower storage is maintained in NN1 with the flood control requirement (hence, an effort is made to maintain head through reduced outflows). The combined effects of altered dam operations, shifts in dry/wet season outflows, and increased evapotranspiration are important when considering the many Mekong River tributaries with similar hydropower development ambitions, and the collective influence that such developments could have on Mekong River flows. For instance, Lao PDR currently has more than ten dams in operation, eight under construction, and 82 under license or in planning stages nationwide, together representing more than 20 000 MW (ICEM 2010). The broader literature is contradictory about the extent to which large-scale development of dams in tributaries of the Mekong could adversely affect ecosystem services (Lu and Siew 2006, Dugan *et al* 2010, Ziv *et al* 2012); any such negative effects, however, would seem to be exacerbated in the case of facility-centered management which would not account for such downstream objectives.

#### 4. Discussion and conclusions

In this paper, we argue that hydro-economic models can be used to provide valuable insights into the cost of non-cooperation in water resources systems. This basic argument is not new, but has not been clearly articulated in the literature with empirical evidence. The conceptual framework we propose for this comparison considers the difference in outcomes achieved by basin-wide optimization versus those produced by facility-specific optimization. This comparative approach shows how water use benefits differ between specific individual users endowed with locational or other advantages and the basin as a whole. In the Nam Ngum basin, we find that the potential gains from coordination of infrastructure management reach 3–12% (US\$12–53 million/yr) of system benefits with modest (6–9% reserve storage) flood control, an estimate that would be expected to increase if the benefits of coordinated selection and sizing of projects, rather than simple management, were included.

To many, these estimates of the value of improved coordination in the Nam Ngum Basin may appear modest. As such, the considerable effort required to derive them might hardly seem worth expending, especially given the likely challenges and costs of implementing institutional arrangements that would deliver them. We would counter such arguments with two points. First, the 10% increase in net benefits from coordinated management of operations in one particular river system within a single country should not be viewed in isolation. Development of institutions that would enable the capture of these benefits would very likely also deliver benefits from other systems within and shared by the same country. Second, and more importantly, little is currently known about the extent to which these findings from



**Table 2.** Per cent difference in hydropower generation by dam under varying precipitation conditions, relative to full coordination.

	Dry year	Wet year	Average year		
			Dry season	Wet season	Annual
Nam Bak 1	−0.4%	0.0%	−4.0%	3.0%	−0.4%
Nam Bak 2	1.2%	0.0%	−9.0%	13.0%	1.0%
Nam Leuk 1–2	1.1%	1.4%	9.0%	−4.0%	1.0%
Nam Ngum 1	−26.0%	−15.0%	−3.0%	−31.0%	−20.0%
Nam Ngum 2	−0.1%	−9.3%	−6.0%	−11.0%	−9.0%
Nam Ngum 3	−1.7%	−2.8%	−9.0%	−8.0%	−9.0%
Nam Ngum 4	1.1%	−0.1%	−13.0%	14.0%	0.0%
Nam Ngum 5	−0.3%	4.5%	−8.0%	8.0%	−0.1%
All dams	−5.0%	−5.4%	−6.0%	−9.0%	−8.0%

Notes: seasonal differences shown for average year only; all results assume a flood control buffer equivalent to 6% of storage capacity.

the Nam Ngum generalize to other basins, and it would be unwise to draw conclusions on the magnitude of losses from sub-optimal management based on this single case. At the same time, multilateral donors and governments have been expending considerable efforts and money to encourage greater negotiation over water resources (Alaerts 1999). It would therefore seem worthwhile for the global community to develop a more systematic understanding of the circumstances under which lack of coordination is particularly costly, using a coherent framework. To develop this understanding, more applications and comparative studies are needed, in large and small basins facing a variety of different types of water resource management problems. Collective action and political economy theories suggest a variety of factors—for example the number of agents, clarity of the existing property rights, degree of spatial and temporal variability and change in the resource, and magnitude and directionality of externalities—that are related to sub-optimal resource management (Ostrom *et al* 1999). The framework for testing these theories in the context of water resources should also be extended to consider the broader (and likely more substantial) costs of non-cooperation, including for example delayed or stalled resource development (Wu *et al* 2013), or sub-optimal choice of infrastructure (Jeuland and Whittington 2014).

Though a detailed review of the limitations of the hydro-economic framework is beyond the scope of this article and can be found elsewhere, we also wish to highlight several important practical problems with their use for assessment of the true costs of non-cooperation, which are also relevant to our model application. First, and not unique to hydro-economic modeling, is the valuation challenge in such an exercise. Errors in accounting for the diversity of potential impacts of different management regimes—particularly non-market ones that are hard to measure and characterize (Jager and Smith 2008, Dasgupta 2013)—may bias estimates of the potential gains from cooperation. Relatively few studies (Ward *et al* 2006 and Tilmant *et al* 2010 are notable examples) incorporate environmental or recreational benefits into model objectives. Indeed, in the example presented here, ecosystem and flood control objectives were only included as minimum flow constraints. Including a more complete set of

downstream impacts and objectives, for example an ecosystem benefit function as a function of flow, could alter the nature of the solution and the economic tradeoffs across coordination scenarios, should the required data become available. Even more generally, prices for water typically do not reflect the marginal value of water, such that econometric, survey, or indirect methods are required to estimate the demand (or marginal benefit curve) for water (Gibbons 1986, Arbués *et al* 2003, Freeman 2003, Jenkins *et al* 2003, Young 2005). The problem becomes even more complex given debates over whether valuation of the benefits from water is even appropriate (Sagoff 1988, Shabman and Stephenson 2000, Smajgl *et al* 2010).

A second objection arises from the potential lack of realism in the specification of economic benefits achievable with and without cooperation, for example due to model misspecification. Our use of a monthly time step in this application ignores the complications associated with management of short-term releases and their potential effects on agriculture (e.g., short-term flood pulse or drought intensification due to release rules aimed at maximizing hydropower). In addition, managers in reality possess imperfect information about future hydrology or human adaptation, and coordination may entail significant transaction costs. Optimization models including stochastic optimization are useful for determining what is best under perfect information or bounded uncertainty, but the complexity of water resource systems means that uncertainty is typically great (Loucks *et al* 1981, Sahinidis 2004). As a result, systems modelers and infrastructure operators may prefer to base decisions on the use of simulation tools that better allow exploration of performance across a range of conditions (Jeuland and Whittington 2014).

Third, when considering systems that are composed of many facility-specific optimizing agents, it may not be appropriate to set river management policy based on optimal expected values as was done here, because the beneficiaries of water-related services are typically risk averse and may be especially worried about water-related outcomes at particular locations in a river basin or about correlated risks across time and space (Philbrick and Kitanidis 1999, Griffin 2006). Uncertainty over future benefits and costs further implies that decision rules based on avoiding downside risk may be more

relevant (Jeuland and Whittington 2014) or that dynamic uncertainty should be modeled more explicitly (Connor 2008). Finally, users and nations typically behave as if water is much more valuable—perhaps for security reasons—than economic calculations would suggest (Whittington et al 2013). To be sure, hydro-economic models can be modified to accommodate these different priorities (Harou et al 2009).

In spite of these important limitations, we believe that additional comparisons such as those provided in this paper would be useful for informing efforts to improve cooperation over water resources.

They offer tangible estimates of the potential gains from coordination, which can be assessed under average or potentially extreme climate conditions. Information on the nature of such cooperative gains can help parties negotiate more favorable water resource outcomes, and discuss issues of compensation for those who may not receive benefits from cooperation. Such information will also become increasingly valuable as climate change increases uncertainty in river basins across the globe.

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